Management of crops on clay soils in the tropics*

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Tropical and sub-tropical regions contain 51 per cent. of the world's land area. This vast region has potential for producing large amounts of food, but the dominant cropping system, shifting agriculture, which is used in much of the tropics, is highly inefficient. Improved practices are adaptable to crop production in tropical regions. With intensive management, favourable yields of many crops are possible. With various forms of multiple cropping, four or five crops can be grown each year on a given tract of land, thereby resulting in higher total yields per hectare than are obtained with intensive management in temperate regions. Although major advances have been made in developing suitable systems for tropical regions, research is needed to conserve soil and water resources further and to develop practices to improve crop production on the highly acid and infertile, difficult to manage, clay textured soils of the tropics.

Keywords: Clay soils; Crop management.

Fifty one per cent. of the soils of the world are in the tropics and sub-tropics (Donahue *et al.*, 1977). The tropics extend from the equator to 23.5° north and south latitude and the sub-tropics extend from the tropical zone to 30° north and south latitude. These vast regions encompass about 7.6 billion hectares of land (Golden Press, 1967).

In the wide expanses of these regions, the climate and topography and the ethnic backgrounds of the inhabitants are highly variable. Precipitation in the tropics ranges from the world record low of <25 mm/year in the Sahara desert to the record high of almost 12 700 mm/year in Hawaii and India. Elevations range from sea level to several thousand metres (Donahue *et al.*, 1977). The over 290 million people of tropical Africa live in 40 countries and represent up to 800 linguistic groups (Okigbo and Greenland, 1976). Many other countries and groups are involved on other continents and islands. The wide range in climate and topography, coupled with the diversity in cultural, economic, colonial, and political background and experience of the population, has resulted in the use of a vast array of crops and cropping sequences. Okigbo and Greenland (1976) reported, for example, that the Medje in Zaire grew 80 cultivars of 30 species of food crops and that up to 156 different crop mixtures were used in the Zaria Province of Nigeria. Included were mixtures of up to six crops.

Although plantation-type agriculture has been developed in many areas, much of the land in the tropics is managed under a system of shifting agriculture or cultivation. This system, which covers about 5 to 6 billion hectares (Lal, 1979), relies on simple technology for crop production. A tract is cultivated until it no longer sustains a farm family. This usually occurs in 2 to 4 years after clearing. The for cultivation. The original tract is cleared and cultivated again in 10 to 15 years. Increasing population pressures and the desire to improve living standards indicate the need for a land management or crop production system that will provide for greater production on a sustained basis (Lal, 1979).

Complete elimination of shifting agriculture should be the ultimate goal. This, however, is not practical in the near future because suitable production systems are not yet available for all regions, soils, and climates, and for economic reasons. Also, implementation of improved, stable crop-production systems will be slow because of the diversity of the population in distribution, customs, and educational level, and because of national priorities and goals (Wortman, 1980). Any gains, however, in increasing the proportion of time in the cultivation–fallow cycle that a tract of land produces enough food to support a family should be important in stabilizing production in areas where shifting agriculture is practised. Such gains are possible through the adaptation of some basic crop production principles to tropical and sub-tropical regions.

With regard to development of production systems for increasing world food supplies, the Technical Advisory Committee of CGIAR (Consultative Group on International Agricultural Research) accorded first priority to research on rain-fed and irrigated croplands of arid and semi-arid tropics, arid rangelands, and infertile lands of sub-humid and humid tropics. Second priority was accorded to research on high rainfall, tropical lowlands and the tropical and sub-tropical highlands (Wortman, 1980). No distinction regarding research priorities will be made in this paper. However, many of the practices discussed were developed in semi-arid regions and, therefore, have greater application to arid and semi-arid regions of the tropics. Practices adaptable to humid regions are included.

The soil orders in tropical and sub-tropical regions that contain appreciable to large amounts of clay are

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Oxisols, Ultisols, and Vertisols. Oxisols and Ultisols develop only in tropical and sub-tropical regions. Vertisols occur most frequently in tropical regions, but may occur in other regions also. Oxisols, Ultisols, and Vertisols comprise 15.9 per cent. of the world's land area (Donahue *et al.*, 1977). Oxisols occur on old, stable, well-drained land surfaces, and occupy about 8.5 per cent. of the world's land area. The clay content in Oxisols is relatively low. The clay has a net positive charge and settles in water as would a fine sand. The clay minerals are mostly mixtures of kaolinite and hydrated oxides of Fe or Al or both. The cation exchange capacity (CEC) and fertility status of Oxisols are low (Donahue *et al.*, 1977).

Ultisols usually are inter-mixed with or on the outer fringes of areas occupied by Oxisols. Ultisols occupy 5.6 per cent. of the world's land area. Clays in Ultisols are alumino-silicates such as kaolinite and some oxides of Fe and Al. The clays have a net negative charge and disperse in water, and their CEC and base saturation percentage are higher than those of Oxisols. The extractable Al percentage of Ultisols is very high, and it is often toxic to plants. Calcium is usually deficient in Ultisols (Donahue *et al.*, 1977).

Vertisols, which occupy only about 1.8 per cent. of the world's land area, have a dark colour, are high in clay, have a very high shrink–swell potential, and occur throughout the tropics and sub-tropics in sub-humid climates having from 640—1020 mm of rainfall and a long dry season. The clay minerals are mostly montmorillonite, and dry weather cracks are numerous. Vertisols have a very high CEC and a high base saturation percentage, and may contain nodules of $CaCO_3$ in the profile. Water infiltration into cracked Vertisols is high initially, but becomes very low after soil swelling. Typical initial and final infiltration rates on Vertisols are 96 and 2 mm h^{-1}, respectively. Corresponding rates are 154 and 84 mm h^{-1} on Oxisols and 237 and 74 mm h^{-1} on Ultisols (Donahue *et al.*, 1977).

Crop management principles

As indicated earlier, many crops are grown in many combinations and sequences in tropical and sub-tropical regions. All crops are not grown on clay soils, but a discussion of the management of such a wide array of crops is beyond the scope of this paper.

For this paper, intensive crop-production techniques on clay soils through use of multiple cropping systems (includes any crop production system in which more than one crop of one or more species is produced on a given tract of land in one year) will be emphasized. Some aspects of crop management, however, many not be unique to clay soils, but may have application to other soils also. The following essential crop management principles, adapted from Sprague (1979), form the basis of the report:

(1) Management of planting materials – the selection, preservation, and treatment of seed and other materials of crop propagation.

(2) Management of land before planting – the destruction or control of unwanted vegetation (land clearing) and other plant pests.

(3) Seedbed preparation – the preparation of a seedbed conducive to germination, seedling emergence and seedling growth.

(4) Planting – the proper placement of seed in soil with respect to planting rate, depth, soil water content and anticipated seasonal environment.

(5) Soil management – the application to soil of corrective measures, such as erosion control and adjustments in drainage, acidity, nutrients, and water content, to promote plant growth and development.

(6) Management of plant pests – the protection of crops from weeds and other natural enemies.

(7) Management of plant products – the harvesting, processing and storing of the products of yield until they are used or marketed.

Management of planting materials

All plant species, whether propagated by seeds, tubers, roots, or shoots, are best adapted to certain climates and soil conditions. Additional restrictions to plant adaptation are imposed by competition for light, nutrients and water, which are especially important in multiple cropping systems. For this paper, only species known to be adaptable to tropical or sub-tropical climates will be considered. These, in general, are species that cannot tolerate low temperatures. The minimum for good growth varies (Wilsie, 1962; Papadakis, 1970), but the freezing temperature is the minimum for plant survival.

Clay content, among other factors, affects the water holding capacity, aeration and drainage of a soil. Many plants are adapted to clay soils provided levels of water, aeration, and drainage are favourable. For example, rice (*Oryza sativa* L.) performs well in flooded soils, whereas banana (*Musa paradisiaca* L.) requires good drainage and aeration for the production of high-quality fruit (Wilsie, 1962). Some tropical and sub-tropical clay soils have a pH of <5 and associated high levels of exchangeable and soil-solution Al, which are toxic to roots of many plants. Some susceptible plants are cotton (*Gossypium* spp.), tomato (*Lycopersicon* spp.), alfalfa (*Medicago sativa* L. subsp. *sativa*), celery [*Apium graveolens* L. var. *dulce* (Mill.) Pers.], maize (*Zea mays* L.), grain sorghum [*Sorghum bicolor* L. (Moench)], and sugar-beet (*Beta vulgaris* L.). Aluminium-tolerant plants include groundnuts (*Arachis hypogaea* L.), pearl millet [*Pennisetum americanum* (L.) Leeke], Bermuda grass [*Cynodon dactylon* (L.) Pers.], Napier grass (*Pennisetum purpureum* Schumach.), and star grass (*Cynodon plectostachyus* K. Schum) (Donahue *et al.*, 1977). The tolerance or susceptibility to Al toxicity of some species, for example, wheat (*Triticum aestivum* L.) (Foy *et al.*, 1965; Lafever *et al.*, 1977), barley (*Hordeum vulgare* L.) (Foy *et al.*, 1965; MacLean and Chiasson, 1966), and soya beans (*Glycine max* L.) (Armiger *et al.*, 1968; Hanson and Kamprath, 1979), depends on the cultivar. Soil testing is an important practice for determining the adaptibility of a particular cultivar to a soil where Al toxicity is a potential problem.

In multiple cropping systems, especially where plants of different species are intercropped, plants must compete for light, water and nutrients. Tall-growing plants that require large amounts of light can be successfully grown with shorter plants that require less light. Likewise, plants with deep, extensive root systems can extract adequate water and nutrients from deep in the soil, yet shallow-rooted crops may thrive on water and nutrients in surface layers of soil. Besides crop responses to multiple cropping, Francis *et al.* (1976) showed that bean species (*Phaseolus* ssp.) responded differently when intercropped with dwarf or normal-height maize (Table 1). Selection for one system may, therefore, not provide the best bean for a different system. Different responses to different systems can be expected also for other crops.

After a desirable plant species or cultivar for a given condition has been selected, the planting material must be preserved and treated until use. Storage of planting materials may be a major problem in tropical regions, especially for seasonal crops. However, storage of the materials for subsequent use on clay soils should require the same management practices as when the materials are used on other soils.

Table 1 Yields of nine climbing bean collections associated with two contrasting maize types, Boliche, Ecuador, 1973 (Francis *et al.*, 1976)

	Beans associated with dwarf maize		Beans associated normal maize	
Climbing bean cultivar	Rank	Yield (kg ha[-1])	Yield (kg ha[-1])	Rank
Panamito	1	1340a[a]	780bc	5
Puebla-421	2	1030b	700cd	6
Aguascalientes-70	3	1000b	1080a	2
Pata de Paloma	4	950b	990ab	4
Guatemala-358	5	940b	1010a	3
Puebla-163	6	880bc	1100a	1
Guanajuato-113A	7	810bc	670cd	7
Puebla-151B	8	800c	540d	9
Aguascalientes-67	9	710c	600cd	8

[a] Bean yields in same column followed by same letter do not differ significantly (5% level)

Management of land before planting

In tropical regions where native vegetation is permitted to grow after the cropping period, the land must be cleared before crops can be grown again.

In the system of shifting agriculture, the slash-and-burn technique of land clearing is widely used. Ashes from burned vegetation provide nutrients for subsequent crops. However, removing all existing vegetation by burning or other methods leaves the soil highly susceptible to erosion, especially on sloping soils (Lal, 1979). Seubert *et al.* (1977) compared the slash-and-burn and mechanical (bulldozer) methods of clearing a tropical forest in Peru. Because nutrients were returned by the slash-and-burn method, this method was better than bulldozing for crop production, even when fertilizers were applied to bulldozed plots. Besides resulting in lower yields, use of the bulldozer caused severe compaction and removed the root mat from the soil, which greatly reduced water infiltration compared with that on burned plots. The burned plots retained their root mat, and the soil surface was protected from rain by ashes and charred materials. Use of bulldozers (for land clearing) only during the dry season should minimize soil compaction. Also, use of a heavy chain between two tractors, tree crushers, or other devices that reduce the area traversed by the machinery or that retain plant materials at the surface should decrease soil compaction (Seubert *et al.*, 1977). Use of herbicides to kill native vegetation may also be feasible, especially when the vegetation is killed well before planting, so that the nutrients are released through decay of the vegetation.

On areas already cleared, unwanted plants must be kept from becoming re-established and weeds must be controlled to avoid their eventual competition with crop plants for light, water, and nutrients. An important consideration in drier regions is that water use by weeds reduces the amount of water stored in soil. The method of weed control, however, can greatly influence rainfall run-off and soil water content. When Lal (1979) compared ploughing and no-tillage on areas with slopes up to 15 per cent. run-off and soil losses from ploughed plots were 9 and 2000 times higher, respectively, than those from no-tillage plots. The no-tillage plots provided a surface cover because the vegetation was killed with herbicides, whereas raindrop impact caused surface sealing on ploughed plots. Another example of the value of surface protection for reducing soil losses by erosion is shown in Table 2 (Williams and Joseph, 1970). Decreasing run-off allows more water infiltration and, therefore, increases the crop production potential in drier regions. In wetter regions with distinct wet and dry seasons, reducing run-off can potentially increase the length of the growing season by conserving water from early or late rains. This may allow earlier crop establishment, reduce water stress during short-term droughts, or allow crops to continue growth longer into the dry season without undergoing severe water stress.

Ploughing has sometimes been advocated for controlling insects and plant diseases. Introduction of conservation tillage (also called zero-, no-, minimum-, and limited-tillage), therefore, caused concern regarding its effect on insects (Musick and Petty, 1973) and plant diseases (Boosalis and Cook, 1973). The concern may be justified because tillage interrupts the life cycle of insects by deep burial or exposure to cold temperatures. The latter reduces populations of the southwestern maize borer [*Diatraea grandiosella* (Dyar)] (Daniels, 1975), and burial of disease organisms with crop residue may decrease subsequent infection of plants (Boosalis and Cook, 1973). Lal (1979), however, reported that stalk borer damage to maize was much greater in ploughed than in no-tillage plots in Nigeria. Also, populations of parasitic nematodes in maize were five times greater in ploughed than in no-tillage plots. According to Phillips and Young (1973), disease problems generally were similar with conventional and no-tillage systems.

Seedbed preparation

A seedbed conducive to seed germination, seedling emergence, and seedling growth is a prime requisite for any cropping system. Some qualities of a good seedbed are favourable water content and temperature, good aeration, a soil condition that provides for good seed-soil contact, absence of crusting and compaction, and freedom from weeds and insects.

Soil water content

Water content of the seed zone is critical for seed germination and seedling establishment. If the water content is too low, seeds may not germinate or may germinate slowly or unevenly, causing uneven seedling emergence and growth. If too high, aeration may be too low for seed germination or seedling growth. Also, high water contents may cause

Table 2 Effect of soil cover on erosion (Williams and Joseph, 1970)

Treatment	Total soil loss in 3 years (t ha^{-1})
Permanent grass sward (protection from raindrop impact and reduced run-off)	7.4
Two layers of mosquito gauze 15 cm above bare soil surface (minimizing drop impact, no reduction of run-off)	6.7
Bare soil	780

planting problems such as adherence of soil to implements, poor traction of wheeled implements, and compaction of soil. Such problems may be especially severe on poorly drained clay soils.

Where excess water is a problem, drainage should be provided. Drainage is normally provided by open ditches or underground pipe lines. However, drainage on a small scale can also be provided by seed-bed configuration. For example, Krantz *et al.* (1978) obtained higher yields in India when crops were planted on beds or ridges than when flat planted (Tables 3 and 4). The beds, which were constructed at a slight grade, provided drainage of the seed-bed, and excess water was removed from the field by accompanying furrows. Because of construction at a slight grade, the bed–furrow system also reduced run-off velocity and provided more time for water infiltration, which helped to conserve water for plant use. Similar conveyance of excess water and water conservation benefits, as well as erosion control, were obtained with a graded-furrow system on Houston Black Clay (fine, montmorillonitic, thermic Udic Pellusterts) in Texas (Richardson, 1973). Planting on beds was also recommended by Bradfied (1969) for intensive cropping where the interval between rains is relatively short. Soil in beds dried more quickly and thus provided a better chance for planting before the next rain, which in monsoon rainfall areas could delay planting for several weeks.

In rainfall-deficient areas, planting is often delayed until rain provides adequate water for germination. Subsequent rains ensure seedling establishment. Even in high-rainfall areas with distinct wet and dry seasons, soil water content before onset of the rainy season may be too low for planting. If extra water could be conserved by use of mulches, better weed control, or improved tillage methods, so that seeds could be planted and seedlings established before onset of the rainy season, overall crop production could be increased by growing crops able to use some of the water during the monsoon season. This would be an improvement over the system of growing crops after the rainy season on clay soils at some locations. At such locations, crops are dependent on water stored in soil and, in some cases, water from ponds and shallow wells (Krantz *et al.*, 1978).

Much research concerning water conservation has been conducted for drier temperate regions, and some of the practices are applicable to tropical and sub-tropical regions. Some applicable practices are run-off control and infiltration enhancement, evaporation reduction, minimal or no soil mixing or inversion, and improved weed control.

Effects of graded furrows and no-tillage on run-off reduction and concomitant infiltration enhancement have already been mentioned. The graded furrows decrease run-off velocity, thus providing more time for infiltration. A recently developed system that controls run-off is the no-tillage system, which provides plant residue at the soil surface, thereby enhancing infiltration because run-off velocity across the surface is reduced. Residue also protects surface soil against dispersion from rain-drop impact, thereby maintaining an unsealed surface that allows water to readily enter the soil rather than run off across the surface. Other practices for controlling run-off include contour furrows, terraces (graded, level, closed-end level, bench, conservation bench), and furrow blocking. Contour furrows are generally used in conjunction with level and blocked-end level terraces to distribute more evenly potential run-off water over a large portion of the field. With bench terraces, the entire area between terraces is levelled to distribute water evenly on the field. This is a common practice in some Asian countries. For the conservation bench terrace system, a portion of the land immediately above terraces is levelled to capture run-off water from the watershed, which is upslope from the levelled area. The different level terraces were developed mainly for sub-humid and semi-arid areas of temperate regions, but should be applicable also to drier tropical regions.

Furrow blocking involves construction of small dams across furrows at relatively short intervals to hold potential run-off water on the field. This practice should be applicable to tropical areas with limited rainfall. In high-rainfall areas, the dams may increase wet soil problems and may overtop, thus increasing erosion. However, blocked furrows on the slowly permeable Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls) in Texas held the water from 145 mm of rain in a 24 h period (Clark, unpublished

Table 3 Effect of land management on crop yields on a deep Vertisol (means for 1976–77 and 1977–78) (Krantz *et al.*, 1978)

	Yield (kg ha^{-1})	
Land treatment	Maize	Chickpea
Flat planting	2 690	650
Narrow (75 cm) ridge planting	2 790	590
Broad (150 cm) bed planting	2 800	830

Table 4 Grain yield as affected by planting method in two cropping systems on deep Vertisols in India (1967–77) (Krantz *et al.*, 1978)

	Cropping system			
	Intercropped		Sequentially cropped	
Planting method	Maize (kg ha^{-1})	Pigeon-pea (kg ha^{-1})	Maize (kg ha^{-1})	Chick-pea (kg ha^{-1})
Bed planted	3 290	760	3 210	600
Flat planted	2 910	620	2 640	360

data). On more permeable soils, greater infiltration should reduce the potential for over-topping of furrow blocks.

Besides controlling run-off, residues maintained on soil surfaces in no-tillage systems reduce evaporation of soil water. This results in surface soil remaining moist for a longer time after rainfall, thereby providing favourable conditions for planting for a longer time (Unger and Stewart, 1976). Evaporation can also be reduced by using mulches. Many mulching materials have been evaluated. Materials that completely cover soils, such as plastic sheets, effectively control evaporation, but may not be practical except for high-value crops. More readily available and relatively effective are mulches of plant materials (leaves, stems and clippings). When such mulches were placed on soil at relatively high rates during fallow, major increases in water conservation through reduced evaporation and enhanced infiltration were obtained (Unger, 1978a). Yields of grain sorghum planted after fallow were increased by the extra stored water (Table 5). Similar benefits from applied mulches were obtained in drier tropical regions (Prihar *et al.*, 1979). As for the no-tillage system, mulches increase water content near the soil surface, thereby improving conditions for germination and seedling establishment. A disadvantage of using mulches is the difficulty in planting through a mulch. For satisfactory planting, a special planter may be necessary or the mulch must be removed, then replaced after planting. When mixed or inverted by tillage, a soil may rapidly lose water by evaporation, especially in dry climates. With the no-tillage system, however, water that would normally be lost due to drying is conserved and, therefore, no-tillage soil is re-wetted with less rain. The amount lost due to tillage is variable and depends on soil type, tillage depth, soil water content at tillage, and extent of subsequent soil drying. For Pullman clay loam in Texas, the author's calculations (unpublished data) show that 40 mm of water is lost from the upper 20 cm of soil when it dries from field capacity (-33kPa matric potential) to the permanent wilting point (-1500kPa matric potential) after tillage. An additional 27 mm of water is lost if the soil becomes air dry, which often occurs. Losses would be less if the soil is ploughed at a lower

Table 5 Mulch rate effects on soil water storage during fallow and subsequent grain sorghum yields, Bushland, Texas, 1973-76 (Unger, 1978a)

Mulch rate (t ha^{-1})	Precipitation storage[a] (cm)	Yield (kg ha^{-1})
0	7.2c[b]	1 780c[b]
1	9.9b	2 410b
2	10.0b	2 600b
4	11.6b	2 980b
8	13.9a	3 680a
12	14.7a	3 990a

[a]Average precipitation during fallow was 31.8 cm
[b]In each column, values followed by the same letter are not significantly different at the 5% level according to the Duncan Multiple Range Test

water content. However, any loss potentially reduces the amount available for crop production.

Timely weed control is essential for maintaining a favourable water content in a seedbed because weeds use water that could be used by crops. Weed control during the entire period between crops is desirable in drier regions so that the soil profile can be filled with water. Although weeds use soil water, water is also lost by evaporation. Tillage may increase water loss by evaporation. Therefore, weed control in drier regions can be delayed until weeds use more water than that lost due to evaporation. In Texas, controlling weeds by tillage at 4 or 10 days after emergence or at 2 week intervals caused no significant differences in water storage during fallow or subsequent wheat or grain sorghum yields. Delaying control until 17 or 24 days after weed emergence decreased water storage and yields (Table 6) (Lavake and Wiese, 1979). When herbicides are used for weed control, they should be used earlier than tillage for effective water conservation because weeds may continue to use water for several days after herbicide application, whereas tillage usually kills weeds almost immediately (Unger, in press). Weed control is even more important as planting time approaches because weed growth at that time can thoroughly deplete the soil water supply, which could reduce germination and seedling establishment or delay planting until the next rain.

Soil temperature

Seeds of all plant species germinate and seedlings grow within some range of temperatures, but most species have an optimum temperature for germination and growth. The optimum for germination, however, may be different from the optimum for subsequent seedling or plant growth (Unger, 1978b).

Temperatures in most tropical and sub-tropical regions are such that minimums seldom interfere with crop production. Even near the 30th parallel of the sub-tropics, the growing season is long enough to allow most crops to reach their full production potential. However, with multiple cropping in some sub-tropical regions, problems could occur with crops sensitive to low temperatures. Likewise, high temperatures could cause problems for some crops. For multiple cropping systems, it is, therfore, essential to select crops that tolerate the expected temperatures for a given region and season.

Some control of seedbed temperature is possible through soil management. A bare soil reaches favourable temperatures sooner than a residue-covered soil (Unger, 1978b). Also, a dry soil warms more rapidly than a wet soil. Therefore, clay soils that retain high amounts of water would warm slower than well-drained sandy soils, which retain relatively small amounts of water. For these reasons, use of plant residue mulches or the no-tillage system sometimes delays planting in cool climates (Unger and Stewart, 1976). However, surface residues also prevent excessively high soil temperatures that could be detrimental to seed germination and seedling establishment. In Nigeria, the temperature was 41°C at the 5 cm depth 2 weeks after planting grain sorghum in clean-tilled soil. Where sorghum was no-tillage planted through 1-2 cm of crop residue, the temperature reached only 31°C. The high temperatures reduced germination and seedling

Table 6 Effect of tillage frequency and timing during 11 month fallow on average number of tillage operations, soil water content and grain yields in a wheat-sorghum-fallow system in Texas (Lavake and Wiese, 1979)

Tillage treatment	For wheat crop			For sorghum crop		
	Tillage operations (avg. number)	Soil water at planting[a] (cm)	Grain yield (kg ha^{-1})	Tillage operations (avg. num)	Soil water at planting[a] (cm)	Grain yield (kg ha^{-1})
Every 2 weeks	10.3	11.8ab	580ab[b]	10.6	9.0a	2 410b[b]
Days after weed emergence: 4	5.3	11.4a	630a	6.1	9.0a	2 600a
10	4.3	10.7ab	580ab	5.1	8.9a	2 530a
17	3.6	9.7b	560ab	4.0	8.4a	2 100bc
24	2.7	9.1b	500b	4.0	7.9a	1 900c

[a] Plant available water determined to a 1.2-m depth
[b] In each column, values followed by the same letter or letters are not significantly different at the 5% level according to the Duncan Multiple Range Test

vigour. Also, yields were 50 per cent. greater with no-tillage because the lower temperatures reduced plant water stress (Rockwood and Lal, 1974). Similar results were obtained by Allen *et al.* (1975b) when sorghum was no-tillage planted in wheat stubble in Texas in July. Maximum temperatures during the emergence period averaged 32°C on no-tillage plots and 38°C on clean-tillage plots. Higher temperatures in clean-tillage plots reduced germination, emergence, and seedling vigour.

Other techniques for controlling seedbed temperatures include soil surface aspect with respect to the sun and use of radiation-absorbing or reflecting materials on the surface. Soils with surface -exposure toward the sun warm sooner than those with exposure away from the sun. Control of surface aspect, therefore, could be used to either increase or decrease seedbed temperatures, depending on crop requirements. Likewise, use of radiation-absorbing or -reflecting materials could increase or decrease seedbed temperatures.

Soil aeration

Soil aeration involves the interchange of oxygen and carbon dioxide between soil and atmosphere. Poor aeration may cause poor germination, seedling development or plant growth, especially in poorly drained clay soils or soils with dense surface layers. Therefore, any practice that improves drainage or prevents formation of dense layers should improve aeration. Soil drainage is an important management factor and has already been mentioned. The no-tillage system, also mentioned, tends to increase soil water contents and, therefore, increases drainage problems, which has delayed producer acceptance of the system on some poorly drained clay soils (Griffith *et al.*, 1973). On well-drained soils, aeration is not a problem with no-tillage because the seedbed water content is sufficiently low. Also, surface residues with no-tillage prevent the formation of dense surface layers after intense rainfall on bare soil (Unger and Stewart, 1976).

Seed–soil contact

Seeds must adequately contact moist soil for rapid imbibition of water. Adequate seed coverage, an aspect of seed–soil contact, reduces damage to seeds and seedlings by birds, rodents and insects (Unger and Stewart, 1976).

Clay soils generally cause no problems with regard to seed–soil contact when they are moist, well-aggregated and friable, but can cause major problems when they are too wet or too dry. The optimum size of soil aggregates for good contact depends on seed size; small seeds require smaller aggregates than large seeds. A desirable soil-aggregate range is 1–5 mm (Raney and Zingg, 1957). Clay soils tends to be cloddy when worked while too dry, and the clods must be broken into smaller units by tillage or weathering before planting. Seed-beds on clay soils in dry regions, therefore, should be prepared well before planting so that clods can be broken down by rainfall. If aggregate size is suitable and weed control is adequate, no further tillage is necessary at planting time. Planting in a clay soil that is too dry tends to result in clods that are too large for optimum seed–soil contact.

Planting in a wet clay soil causes problems when the soil is sticky or when openers will not penetrate to the proper depth. This may be a problem even when planting is done with hand tools. The wet soil may still supply adequate water to seeds, but germination and seedling establishment may be reduced when seed coverage is poor or when environmental conditions are conducive to rapid soil drying.

Poor seed–soil contact has been a major problem with no-tillage systems where crops are planted through surface residues or into sod. While conventional planters are designed to operate in soil virtually free of surface residues, no-tillage planters must cut through surface residues or sod, open a slot in the soil, place the seed, cover the seed, and firm the soil over the seed. Problems with no-tillage planters arise mainly in cutting the residues or sod and from inadequately covering the seed. The planters normally have coulters to cut residues, but residues may be pushed into the soil, especially if the soil is wet. When this occurs, subsequent seed coverage and contact with soil often is poor. Poor coverage and contact also occur when a slot is cut into relatively firm soil and there is not enough loose soil to cover the seed adequately, or when the press wheel fails to close the slot around the seed. A compensating factor for poor seed-soil contact with no-tillage planting is the higher water content in the seed zone, which supplies more water to the seed. Also, the water content remains higher for a longer time because of slower evaporation.

Soil crusts

The major adverse effect of soil crusts is interference with seedling emergence (Grable, 1966), but crusts or dense surface layers with high water content may also reduce germination and seedling emergence through reduced aeration (Unger and Stewart, 1976). Crusts develop when raindrops strike bare soils, causing dispersion and re-orientation of soil particles. Crusts also develop when irrigation or flood waters disperse low-stability aggregates or deposit sediments. Seedlings of different species vary widely in their ability to emerge through crusts. Maize seedlings often emerge by lifting large portions of crusts (Grable, 1966), whereas cotton seedling emergence is highly dependent on crust strength (Bennett *et al.*, 1964; Wanjura, 1973). Seed size of both species is similar. Seedlings of small-seeded crops are especially vulnerable to emergence problems due to crusting.

The adverse effects of soil crusts can be minimized by maintaining the soil in a moist condition, provided that this will not result in an aeration problem. The moist condition can be accomplished by light sprinkler irrigation at relatively frequent intervals or use of the no-tillage system. Crusting can be largely avoided by protecting the surface soil against dispersion due to raindrop impact. Surface residues from mulches or those remaining from previous crops in no-tillage systems harmlessly dissipate the energy of falling raindrops, thereby reducing soil dispersion and crusting. For example, 80 mm of intense rain after planting grain sorghum and soya beans, followed by hot, dry winds, caused a dense crust on conventional-tillage plots. Sorghum seedlings emerged through the crust, but soya bean seedlings did not. In contrast, a near-perfect plant population of both crops was obtained in no-tillage plots (Sanford *et al.*, 1973).

Soil compaction or density

For efficient soil water and nutrient use by plants, extensive root systems have been considered essential. For deep root development, soils free of compact layers and dense horizons are important, and tillage is widely used to remove restricting layers from near the surface. Gill and Trouse (1972), however, showed that plants grew and yielded well even when the idealized seedbed conditions once considered essential were not provided, if field traffic was restricted to specified zones. When traffic is not restricted to specified zones, improved conditions created by tillage are often negated by subsequent tillage. This situation is aggravated by frequent trips across the field. Consequently, by the time of planting, much of the surface has been traversed by a tractor or implement with resultant increases in soil density. Reducing the number of field operations and restricting traffic to specified zones should maintain better soil conditions for planting and seedling establishment (Unger and Stewart, 1976).

Soil of sufficient density reduces or restricts root growth. The restriction, however, is dependent on soil water content (Taylor *et al.*, 1967). Because water contents are generally higher with no-tillage than with conventional-tillage systems, higher soil densities apparently are less critical with the no-tillage system, except where poor aeration may be a problem. Higher water contents near the surface suggest that deep rooting may not be as important where no-tillage rather than conventional tillage is practiced.

Weed control

The value of weed control for conserving seedbed water was previously mentioned. Weed control is also important with respect to the planting operation, plant nutrients, and competition between weeds and seedlings for light and space.

Weeds use plant nutrients. If weeds have not been controlled, some nutrients needed for the crop will have been absorbed by the weeds and, therefore, will not be available to the crop until the weeds decompose. The weeds may decompose too late in the crop's growing season to benefit the crop. Thus, timely weed control is essential for crop plants to have the full benefit of all available nutrients.

Insect control

Soil-borne insects may destroy seeds and seedlings, thereby damaging or completely destroying a crop. Where insects cause problems, use of chemically-treated seed may overcome the problem. Other techniques for controlling insects are applying chemicals before, during, or after the planting operation; planting insect-resistant species or cultivars; rotating crops; destroying alternate host plants; shifting the growing season, thus planting before or after the anticipated time of major insect problem; and destroying the habitat of insects during the non-destructive phase of their life cycle (Litsinger and Moody, 1976).

Planting

Selection of adapted species or cultivars and preparation of a favourable seedbed are of little value in crop production unless the seeds (includes other means of plant propagation) are properly planted with respect to rate, depth, soil water content, and anticipated environmental conditions.

Rate

Factors influencing the optimum planting rate for a given species or cultivar include the expected percentages of seed germination and seedling emergence; the plant's growth habit, available water supply and adaptability to surrounding plants; and the intended use of the plant products.

The germination percentage stated by the seed vendor is a good guide for determining planting rates. When the germination percentage is not stated, an estimate can be obtained by germinating a representative sample of seed on moist paper or cloth or in moist soil.

In contrast to germination percentage, emergence percentage is more difficult to establish because many factors influence emergence. However, if viable seed is planted in a well-prepared seed-bed, a high percentage of seed should produce seedlings. A major deterrent to seedling emergence is soil crusting due to rainfall. When a soil crusts, mechanically breaking the crust may still allow favourable seedling emergence. Once expected germination and emergence percentages are established, the planting rate should be adjusted accordingly to obtain the desired plant population.

A plant's growth habit strongly influences the optimum planting rate. Plants with a branching growth habit or large leaves, such as many broad-leaf species, normally are planted at lower rates than those with little or no branching, such as maize or cereal crops. The cereal crops – wheat, oats (*Avena sativa* L.) and barley – may, however, tiller profusely if planted at low rates and thereby compensate for low populations if conditions are favourable.

Planting rates should be adjusted to expected available water supplies. With anticipated high rainfall, such as the rainy season in high-rainfall regions, or a reliable source of irrigation water, planting rates can be higher than when a water deficit is expected during the growing season.

In multiple cropping systems, especially with inter-cropping, competition between plant species for light, water, and nutrients may affect the optimum planting rate. When inter-cropping, species with similar rooting habits, heights, canopies, and light requirements should be planted at total rates similar to the optimum for either species alone. For species with different requirements, somewhat higher populations are possible (Francis *et al.*, 1976; Trenbath, 1976).

Some species adapt readily to differences in plant populations and, within limits, produce similar yields, regardless of population. Seed yield of several cultivars of irrigated sunflower (*Helianthus annuus* L.), for example, was not significantly affected when planting rates were doubled and decreased only slightly when they were quadrupled (Unger *et al.*, 1975). However, the increase in planting rate caused a marked decrease in seed size. With excessively high populations, sorghum grain yields were lower than with a lower population, but forage yields were higher (Allen *et al.*, 1975a). Although not important for some crops, size of edible seed, fruit, or tuber may be important for others. When important, the planting rate should be adjusted to a level that allows the plant to yield a product of a desirable size.

Depth

Small-seeded crops are normally planted shallower than larger-seeded crops. Major requirements, regardless of seed size, are that seed be placed in moist soil and that the soil remain moist until seedlings become established. Because clay soils retain and more readily transport water than sandy soils, planting can be shallower on clay soils. Shallow planting should also be beneficial on clay soils if rain falls before seedling emergence. When rain falls, seedling emergence may be decreased due to poor aeration or crusting, especially on poorly drained soils on which it would be difficult to break the crust mechanically. Where surface protection is provided, as by mulches or growing crops in inter-cropping systems, shallower planting may give good results. The mulch or plant canopy provides for slower soil drying and, therefore, conditions are favourable for germination and emergence for a longer time than in a bare soil (Rockwood and Lal, 1974; Sanford *et al.*, 1974; Unger *et al.*, 1971; Unger, 1978a).

Soil water content

Soil water content at planting, besides influencing planting depth (seed coverage), also is a determining factor in deciding whether seeds should or can be planted on the ridge or in the furrow. Requirements vary among species. Rice, for example, tolerates flooded conditions after establishment and is widely grown in flooded soil. Crops that do not tolerate flooding should be planted on beds (Bradfield, 1969). In semi-arid regions, where there is little danger of prolonged flooding, crops such as cotton and grain sorghum are often planted in furrows where the soil is moist (Unger, in press).

Soil water content, in conjunction with anticipated rainfall, influences what crops can be grown and their planting dates. Crop selection has been discussed. For highest production potential, crops should be planted at a time compatible with the expected growing-season rainfall. Crops that tolerate prolonged rainfall should be planted before or early in the rainy season. For regions with distinct dry and wet seasons and where the onset of the rainy season is abrupt, crop establishment may be difficult before the rainy season starts. Dry planting before onset of the rainy season has been successful in India (Krantz *et al.*, 1978). Also, use of practices that conserve sufficient water from the previous wet season or the limited rainfall before onset of the rainy season would be especially beneficial for crop establishment, in addition to the recognized benefits of these rains for land development and seedbed preparation (Krantz *et al.*, 1978; Prihar *et al.*, 1979). Mulches of crop residue or other materials, or even of dry soil (Bolton and de Datta, 1979), may conserve adequate soil water for early crop establishment. In regions with irrigation water, early irrigation and planting could cause the crop to be more advanced when rain falls, thus allowing better use of the rainfall for production.

Crops that tolerate prolonged rainfall can also be planted as conditions permit during the rainy season. Bradfield (1969), for example, advocated planting on beds that dry rapidly between rains, thus allowing crops to use subsequent rainfall effectively. Drought-tolerant crops often are planted at the end of the rainy season and are highly dependent on stored soil water and, where available, water from ponds and wells. Use of management practices that conserve adequate amounts of late-season rainfall is important for good yields of crops that extend into the dry season (Krantz *et al.*, 1978; Prihar *et al.*, 1979).

Environmental conditions

The effect of water availability and occurrence of the rainy season with respect to planting has already been mentioned. Other environmental factors influencing planting include temperature, solar radiation, and day length. Temperature fluctuation throughout the year is slight in the tropics and increases with distance from the equator (Nicholaides, 1979); therefore, temperature influences, more strongly, planting in sub-tropical than in tropical regions. For optimum production, crops should be planted when temperature conditions are favourable for the given species. Because shading from mulches or other plants reduces soil temperature (Sanchez, 1977; Unger, 1978b), mulching or inter-cropping may extend the range of adaption or growing season of a crop. No special management should be necessary on clay soils.

Average solar radiation is higher in the tropics than in temperate regions on an annual basis, but daily radiation during the summer growing season is higher in temperate regions because of the longer days (Nicholaides, 1979). Daily radiation at crop level is reduced by cloud cover and thus is lower in higher-rainfall areas. Interception of radiation by a particular species in an inter-cropping system is also dependent on the species' height in relation to surrounding plants. At Yurimaguas, Peru, with 2137 mm of rain per year and no dry months, monthly solar radiation averages 306 Langleys per day. At Los Banos, Philipines, with 1847 mm of rain per year and four dry months, solar radiation averages 366 Langleys per day for the year and averages 417 and 341 Langleys per day during dry and wet months, respectively. In tropical forests, solar radiation reaching the soil surface ranges from 4–15 per cent. of that reaching the surface in a cleared area (Nicholaides, 1979; Sanchez, 1973). Shifting planting dates so that crop growth or reproductive stages coincide with periods of favourable solar radiation has potential for increasing crop yield. Likewise, crops that tolerate low radiation levels can be planted after crops that require more radiation have been established.

Day length is critical for some crops; these should be planted at a time so that days at the critical growth stage are long enough for the plant to complete its life cycle. Annual day-length variation ranges from zero at the equator to 2 h 50 min at 23.5° latitude. Variation is even greater in sub-tropical regions (Nicholaides, 1979). Selection of planting date for optimum day length, therefore, is impossible at the equator, but becomes important with distance from the equator.

Soil management

Two major goals of soil management systems are to prevent soil deterioration and to attempt improvements in the soil system that result in increased crop production (Peterson, 1979).

Many facets of management could be discussed. Soil erosion control has already been discussed, and drainage has been discussed elsewhere in this paper. Therefore, this discussion will be limited to management of soil acidity, nutrients and water content as they relate to plant growth and development.

Acidity

Low soil pH, usually <5.0, is a common characteristic of many humid tropical and sub-tropical soils (Nicholaides, 1979; Sanchez, 1977; Donahue *et al.*, 1977). Associated with the low pH are high levels of exchangeable and soil-solution Al, which are toxic to roots of many plants. This toxicity limits plant rooting depth, thus allowing water stress in plants while deeper layers of soil contain adequate amounts of water.

Two management schemes are available for overcoming the adverse effects of low soil pH and high exchangeable Al. One is the use of plant species or cultivars that tolerate high levels of Al. This has been discussed in the section on management of planting materials. The second scheme, liming to increase pH and reduce Al toxicity, has been extensively researched and discussed. Results of numerous studies were summarized by Sanchez (1977).

Liming to a pH of 7.0 is not practical for many tropical clay soils because of their high buffering capacity. An adapted practice is to apply lime at a rate of 1.65 t ha^{-1} per milliequivalent (meq) of exchangeable Al/100 g of soil, which raises the pH to $\approx$5.5. This practice effectively precipitates the Al and thereby eliminates the toxicity problems. Lime application at 2 t ha^{-1} resulted in near-maximum maize yields on a soil with low exchangeable Al (1.1 meq of Al/100g). Incorporation of lime to 30 cm resulted in higher yields than incorporation to 15 cm for the first crop, but yields for the fifth crop were little affected by incorporation depth when no additional lime was applied. Lime incorporation to 30 cm is recommended for soils with excellent structure, such as the Oxisols, but not for Ultisols, which have a marked textural change in the upper 30 cm (Sanchez, 1977).

Nutrients

Many humid tropical soils are highly deficient in such essential plant nutrients as N, P, K, Ca, Mg, Zn, Cu, Mo, and B. In a system of shifting agriculture, the nutrients, except N, are supplied from the burned vegetation, but the fertility greatly decreases after one or two crops. For sustained crop production, Sanchez (1977) reported that all nutrients except P could be profitably applied by fertilization. Proper soil tests were available for all nutrients except N, for which field testing was required.

Phosphorus fixation in some soils with more than 35 per cent. clay in the topsoil is severe and increases with increasing clay content. Large amounts of P are needed to overcome the P fixation problem, and this is usually the most important economic constraint to crop production on these soils. Sanchez (1977) discussed the management strategy for coping with P fixation. Components of the strategy are to (*a*) increase P application efficiency by determining which rates and methods give best residual effects, (*b*) use P sources that are cheaper than superphosphate, (*c*) use cheap amendments to decrease P fixation, and (*d*) use crops that tolerate low levels of available soil P.

(*a*) *Application efficiency.* In Brasilia, broadcast application of P was better than banding because plant rooting was restricted to the zone where the P was applied, thus the plants in banded areas underwent greater water stress. Also in Brasilia, broadcast application of superphospate at rates up to 600 kg of P_2O_5 ha^{-1} was profitable for soya beans, but yield was 80 per cent. of maximum with approximately half that rate. A promising strategy is to broadcast 320 kg of P_2O_5 ha^{-1} initially and band 80 kg of P_2O_5 ha^{-1} before planting each crop, including the first (Sanchez, 1977).

(*b*) *Cheap P sources.* Direct application of rock phosphate may be more effective and economical than use of superphosphate, but rock phosphates differ in their reaction with acid soils. A highly reactive rock phosphate from North Africa was equal to superphosphates on some Souh American soils, but a South American rock phosphate (Araxa) did poorly unless it was fused with magnesium silicate, which raised its cost to that of superphosphate. Effectiveness of untreated Araxa rock increased with time (Sanchez, 1977).

(*c*) *Cheap soil amendments.* Application of lime and calcium silicate at rates just sufficient to neutralize the exchangeable Al decreased the amount of P required to provide 0.03 ppm of P in the soil solution by 41 and 46 per cent. respectively. These amendments were less effective at higher levels of soil-solution P, which led to the conclusion that the decrease in P fixation from liming is considerable only in acid soils with a high percentage of Al saturation (Sanchez, 1977).

(*d*) *Plants that tolerate low P.* Some cultivars of maize, beans and rice tolerant of P stress yielded from 63-78 per cent. of the minimum yield obtained without stress; cultivars susceptible to P stress yielded only 22-37 per cent. of the maximum under similar conditions. The mechanism responsible for tolerance to low soil P is not well understood, but may be related to plant tolerance of high Al levels (Sanchez, 1977).

Water content

Low water-holding capacity and restricted rooting depth due to Al toxicity make plants highly susceptible to short-term droughts on some tropical soils. In Brasilia, for example, where there is a 50 per cent. probability of having at least 14 continuous rainless days during the rainy season each year, maize wilts after 7 days without rain. When the drought occurs at critical growth stages, maize yields are decreased by an average of 54 per cent. (Sanchez, 1977).

Adverse effects of drought can readily be overcome by irrigation where water is available. Irrigation from streams or ponds also allows crop production to extend into or during the dry season (Krantz *et al.*, 1978; Sanchez, 1977). Where water is not available for irrigation, soil liming to promote deeper root development and use of mulches to decrease evaporation can reduce water stress during drought. When both practices were used in Brasilia, maize yields were increased by ≈ 27 per cent. when an 18 day drought occurred at the maize's critical growth stage during the rainy season. Mulching reduced evaporation of soil water by 4–7 mm day^{-1}, and liming to 30 cm allowed deeper root growth and soil water extraction than where the soil was limed to 15 cm (Sanchez, 1977).

Management of plant pests

Plant pests include any organisms that interfere with the normal growth, development, and yield of crop plants. Included are weeds, insects, diseases, animals and birds.

Weeds

Weeds, which compete directly with crops for water, nutrients and light, have been discussed previously. Effects on crop yields are related to weed density and plant competition. Shipley and Wiese (1969) showed that one pigweed (*Amaranthus* spp.) plant per 30 cm of row in irrigated grain sorghum decreased grain yields by ≈ 48 per cent. (Table 7). The importance of good weed control, therefore, is obvious.

Weeds among crop plants are controlled by hoeing, cultivation, or herbicides. Mechanical weed control in multiple-cropping systems, especially mixed inter-cropping, may be difficult. However, the mixed systems tend to decrease weed problems (Nicholaides, 1979; Sanchez, 1977). Weed problems are reduced also when different crops are grown in rotation as compared with continuous cropping of one species because the growth cycle of the weeds is disturbed (Litsinger and Moody, 1976).

Table 7 Effect of pigweed (*Amaranthus* spp.) on sorghum grain yield on Pullman clay loam in Texas, 1966 (Shipley and Wiese, 1969)

Weed spacing in row (cm)	Weed dry matter yield (kg ha^{-1})	Grain yield (kg ha^{-1})	Yield reduction[a] (%)
No weeds	0	5 470	0
240	2 870	4 580	16
120	4 250	3 980	27
60	7 160	3 390	38
30	8 610	2 870	48
15	12 300	2 110	61
7.5	13 300	1 390	75

[a] Reduction in weedy area relative to area with no weeds

Insects and diseases

The best defence against insect and disease problems is to grow cultivars that resist or tolerate the insects or diseases. Other defence mechanisms are to rotate crops or grow them in mixtures and to destroy alternate host plants of the organisms. As with weeds, inter-cropping reduces insect and disease problems (Litsinger and Moody, 1976; Nicholaides, 1979; Sanchez, 1977). Insect and, to some extent, disease problems in established crops can be controlled by chemicals, by hand on small areas, and by introduction of natural enemies of the damaging organism (Litsinger and Moody, 1976).

Animals and birds

Small animals are difficult to control in any cropping system and may be especially troublesome in systems that provide extra shelter, such as the no-tillage system, which provides surface protection and little soil disturbance, and inter-cropping systems, which provide an all year round cover of growing crops. Large animals can usually be controlled by fences or by herding. Birds may be especially troublesome when crops are grown near wooded areas. On limited areas, bird damage may be reduced by use of lightweight plastic netting.

Management of plant products

A crop should be harvested as soon as it reaches the stage of maturity compatible with its intended use. Any delay in harvest lowers the quality, especially that of crop harvested in the immature state. Harvesting may involve considerable traffic by tractors, harvesting machines, trucks, wagons, or even humans in the field to gather and remove the products, which often cause severe compaction. On pasture land, traffic by animals can also cause severe compaction (Bryant *et al.*, 1972).

Ideally, to minimize compaction, crops should be grown during the rainy season or with irrigation, so that plants will not undergo water stress, mature late in or after the rainy season, and be harvested during dry weather. Such management is practised where irrigation is the main water supply and where crops are planted near the ends of or after the rainy season, with the crop being dependent on stored soil water (Krantz *et al.*, 1978). However, where several crops are grown during the rainy season, either in rotation or inter-cropped, or where there is no pronounced dry season, crops must be harvested from wet soil, thereby contributing to soil compaction. To minimize compaction on a field basis, heavy traffic should be restricted to specified areas as much as possible. On small areas, this can be achieved by restricting tractors and wagons to edges of fields and manually carrying the products to transporting vehicles. On larger fields or plantations, multi-row harvesters should be used to gather the crop, with traffic by transporting vehicles restricted to several specified zones. More frequent emptying of harvester bins could reduce the intensity of compaction by decreasing he total weight of the harvester.

After harvest, subsequent processing and storage of products depend on, among other factors, the stage of maturity, intended use, and moisture conditions of the crop at harvest. Crops harvested for fresh consumption or preservation (canning or freezing), such as fruits and vegetables, must be quickly processed, then marketed, used or preserved. For mature crops, such as nuts and grains, rapid processing may not be as essential, and type of processing will be influenced largely by whether the products are for human or animal consumption, and whether they are to be sold or used by the producer.

Crops harvested in humid climates and rainy weather may require special handling before storage because of the high moisture content at harvest. For prolonged storage, grain and similar crop products must be dried to a low enough moisture content to prevent overheating and moulding. Also, precautions be taken to avoid insect and rodent damage to the stored product.

Accomplishments and requirements

Much has been accomplished regarding the development of practices that could stabilize crop production in tropical and sub-tropical regions. Yet much remains to be done, especially regarding practices that conserve soil and water resources and are economically feasible.

Accomplishments

The literature contains numerous examples of the large crop production potential on tropical and sub-tropical soils when they are intensely managed for high yields. A few studies will be highlighted to illustrate this potential.

A year-round growing season, short-season crops and intensive cropping systems allow the growing of four or more crops per year on the same land in the Philippines. For maximum production with multiple cropping, Bradfield (1969) attempted to minimize the time the land was idle. To attain these goals, he recommended: (*a*) Bedding the land to accerlerate drying of the bed tops. (*b*) Keeping tillage operations and the volume of soil stirred to a minimum. (c) Using early-maturing cultivars capable of producing high yields per hectare per day. (*d*) Growing ratoon crops when feasible. (*e*) Transplanting slow-growing vegetable crops. (*f*) Seeding rice directly into unpuddled soil. (*g*) Growing some crops each season which can be harvested in an immature state. (*h*) Intercropping whenever possible. By using some of these principles, Bradfield (1969) squeezed a five-crop system requiring 413 days of growing season into a 12 month period by inter-cropping. Two major land-preparation operations were used annually. Average yields were: rice, 5.0 t ha^{-1}; sweet potato, [*Ipomoea batatas* (L.) Lam.], 25.0 t ha^{-1}; soya beans (dry), 2.5 t ha^{-1}; sweet corn, 40 000 ears ha^{-1}; and soya beans (green pods), 6.0 t ha^{-1}. In another system, Bradfield (1969) produced 22.6 t of grain ha^{-1} in 12 months on the same land. Crop yields were: rice, 5.0 t ha^{-1}; sorghum, 5.5 t ha^{-1}; sorghum (first ratoon), 6.6 t ha^{-1}; and sorghum (second ratoon), 5.5 t ha^{-1}. Ratoon crops did not require additional land preparation.

To supply a variety of foods for the family, some subsistence farmers of Indonesia and Nepal grow 50 to 60 plant species in the homestead areas. Such systems may include: five or six tall-growing trees [coconut (*Cocos nucifera* L.) or fruit], five or six medium-height trees, five or six bushes or shrubs, four or five root crops, and up to 30 shade-tolerant short-statured or vine-type annuals (Harwood and Price, 1976).

In Peru, an intensive inter-cropping system was established after harvesting rice. Maize was planted in 2 m spaced rows, and soya beans were planted on 0.5 m spaced rows between the maize rows. After 45 days, cassava (*Manihot esculenta* Crantz) cuttings were planted in the maize rows. After harvesting maize and soya beans, cowpeas [*Vigna unguiculata* (L.) Walp. subsp. *unguiculata*] were planted where the soya beans had been, while cassava grew vigorously. The four crops grown on the same land required 266 days. After a one month rest period, maize was planted again as before, but upland rice replaced soya beans. After 68 days, cassava was planted in the maize. Maize was harvested after 105 days and rice after 140 days. Groundnuts were planted 5 days after harvesting rice and harvested 3 months later. Cowpeas were grown after groundnuts and before the cassava canopy closed in. The five crops were grown in 367 days. Considering the whole system, nine crops were harvested from the same land in 21 months (Sanchez, 1977).

Requirements

Although considerable progress has been made in developing cropping systems suitable for tropical and sub-tropical regions, additional research is needed to conserve more effectively the soil and water resources of these regions, and to stabilize crop production, thereby increasing world food supplies and improving the living standards of the many inhabitants of these vast areas. Some ideas for research with brief comments are:

(1) What are the practical limits from an economic viewpoint to adopting alternative cropping systems that are more conservative of soil and water resources?

(2) Are there alternatives to burning of native vegetation to release nutrients for crop production? Since burning may cause severe erosion and clearing land with bulldozers causes compaction, could herbicides be used? Would fertilization of the first few crops provide adequate nutrients and would decay of the native vegetation and crop residues then release enough nutrients to result in an equilibrium condition that would eliminate the need for further burning? An equilibrium is reached in 5-8 years after return to forests (Sanchez, 1973). Would this also occur in an intensely managed cropping system without burning?

(3) Is it practical to lime acid soils to greater depths or apply mobile liming materials that would move to greater depths so that plants could root deeper and

thereby extract more water from soil?
(4) Is it practical or economic to develop more water storage reservoirs to conserve run-off water for use during the short-term droughts or during dry seasons?
(5) How can native plants become re-established on soils that are too infertile to produce crops? Are N-fixing or low-P-tolerant plants involved? What is the source of P for the native plants?
(6) What are tolerable levels of soil loss under tropical and sub-tropical conditions?
(7) Is it possible or practical to further select or breed plants that are tolerant of acid soils (high Al levels) and low-P soils?
(8) Are there native or adaptable legume species that can supply adequate N to other plants in mixed intercropping systems? What management is required to obtain maximum benefit from these legumes with respect to providing N to other plants?

Discussion

L. Goberdhan With seedbed preparation in an effort to prevent crusting and maintain crumb structure have you had any experience using petroleum mulches?
Author I personally have not worked with petroleum mulches because they are not practical or economical for the crops we grow. However, they have resulted in favourable seedbed conditions in some instances, based on the literature.
B. Cooper Could you comment further on the matter of deep liming methods and use of alternative liming materials, given the difficulty of incorporation in heavy clays and the large amounts of lime required.
Author I do not have answers to your questions but maybe someone from the audience would like to comment.
B. Greacen (Comment on question by B. Cooper). Tube dispensers attached immediately behind the chisel tines make the application of lime deep within heavy clays very possible.
F.A. Gumbs (Comment on plastic mulch re Dr Unger's presentation). In the Department of Soil Science at UWI we compared black, clear and white opaque plastic with and without overhead shelters and with trickle irrigation. Our experience was that the soil temperatures at 2–4 inches depth never exceeded 35°C and the performances of the crops tested (tomato, cabbage, cauliflower and sweetpepper) were much better under overhead shelters than in the open air. The present cost of overhead shelters would however make its use for crop production prohibitive.

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